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Features
posted June 28, 2002

Using Chondrites to Understand the Inside of Asteroid 433 Eros

--- Data from ordinary chondrite meteorites and from the NEAR mission suggest that asteroid 433 Eros is heavily fractured.

Written by Linda M. V. Martel
Hawai'i Institute of Geophysics and Planetology

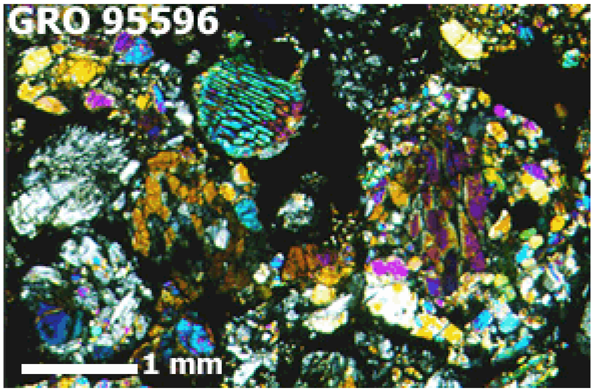
Asteroid 433 Eros is one of the most closely scrutinized chunks of rocky debris in our solar system. We know about its bulk properties, internal mass distribution, and the shape, composition, and mineralogy of the surface from instruments on the Near Earth Asteroid Rendezvous (NEAR) Shoemaker spacecraft. Using mass and volume measurements scientists determined the bulk density of this asteroid for the first time. An interdisciplinary research team with expertise in cosmochemistry, planetary geology, remote sensing, and orbital dynamics compared this orbital information with density and porosity data from meteorite samples to estimate the porosity of the asteroid. Sarah Wilkison and Mark Robinson (Northwestern University), Peter Thomas and Joseph Veverka (Cornell University), Tim McCoy (Smithsonian Institution), Scott Murchie and Louise Prockter (Applied Physics Lab), and Donald Yeomans (Jet Propulsion Lab) report a macro (structural) porosity for Eros of approximately 20%. They compared this estimate with features seen on the surface of Eros and with previously proposed models for the formation of asteroids to conclude that Eros has been heavily fractured by impact collisions but was not demolished to the extent that it is now a rubble pile.

Reference:

Wilkison, S. L., Robinson, M. S., Thomas, P. C., Veverka, J., McCoy, T. J., Murchie, S L., Prockter, L. M., and Yeomans, D. K. (2002) An estimate of Eros's porosity and implications for internal structure. Icarus, v. 155, p. 94-103.

Density of Eros

The NEAR Shoemaker spacecraft thoroughly photographed Eros during its year-long mission. Using countless images, Joe Veverka and Peter Thomas and their colleagues painstakingly determined the total volume of this elongated object. Don Yeomans and colleagues made a careful analysis of the spacecraft's orbit around Eros by analyzing radio signals. This allowed them to determine the total mass of the asteroid. With the volume and mass known, it is easy to calculate the density. The bulk density of Eros is 2.67 ± 0.03 g/cm^3. This value seems to be nearly uniform throughout the asteroid based on NEAR Shoemaker gravity data and implies little variation in its global composition. That composition most closely resembles ordinary chondrite (OC) meteorites based on the chemical, mineralogical, and magnetometer data from NEAR Shoemaker.



Thin section of chondrules and chondrule fragments in a dark matrix under cross-polarized light. Antarctic meteorite GRO 95596, an LL3 ordinary chondrite.

These meteorites, composed of tiny metal and silicate grains and melted silicate particles called chondrules, represent primitive asteroids that never melted. A little bit of melting on Eros, however, cannot be ruled out completely, but available data suggests that surface-altered OCs exposed to space weathering best match the properties of Eros. [See **PSRD** article: The Composition of Asteroid 433 Eros.] Despite this correspondence with OC meteorites, it surprised no one that the bulk density of Eros did not match the average value for OCs (3.40 g/cm3). Eros's density is lower. It's assumed that cracks and voids exist inside the asteroid due to innumerable impact collisions. Some early predictions placed Eros in the "reassembled rubble-pile" model wherein the asteroid is a pile of gravitationally bound fragments from earlier catastrophic smashes. For a review of this model see **PSRD** article: Honeycombed Asteroids. Just how much empty space is there inside Eros? The answer is based on porosity data from ordinary chondrites.

Porosity of Eros

Wilkison and team used two sets of density and porosity data for ordinary chondrite meteorites from Consolmagno and Britt (1998) and Flynn and others (1999) as their starting point to estimate the porosity of Eros. The 42 ordinary chondrite meteorites in the datasets range in porosity from 0 to 23% and have a median porosity of 6%. The team eliminated two meteorites with textures rarely seen in OCs and chose an OC porosity range of 0 to 15% (a range of overlap in the two datasets.) This porosity is defined as microporosity because it refers to the voids and cracks between mineral grains in the meteorite rock samples. Using the average bulk density of OCs, 3.40 g/cm^3 and microporosities between 0 and 15%, the team calculated grain densities of OCs from 3.4 to 4.0 g/cm^3. They compared these meteorite grain densities with Eros's bulk density of 2.67 g/cm^3 to arrive at Eros's total porosity: 21 to 33%. Using the median value of 6% microporosity of OCs, the average bulk density of OCs, and the bulk density of Eros, the team estimated the total porosity of Eros as 26%. If you assume that microporosity is too small-scaled to affect an asteroid's cohesive strength, then the 6% microporosity can be subtracted from the total porosity of Eros to result in a macroporosity (all fractures and voids larger than the mineral-grain sizes) for Eros of 20%. The macroporosity is the key to understanding the impact history of Eros.

Asteroid Structural Changes through Time

The porosity of an asteroid is the result of a long, complicated history. It depends on the initial composition and physical state of the asteroid and on the intensity of the largest impacts that it suffered. The impact history probably dominates the final porosity. Wilkison and her coworkers identify three main categories of internal structures of asteroids, as summarized in the table below. In the most mild case the asteroid is fractured, but still coherent. Impacts have jarred its surface and seismic waves from the point of impact cause fracturing, but the body is still largely a single solid mass. No big chunks of the interior have moved relative to adjacent regions. Its porosity ought to be similar to individual pieces of asteroids, as sampled by meteorites. If the asteroid were made of rock like ordinary chondrites, the porosity would be 0 to 15%.

Asteroid Structural Models			
Model	**Coherent but Fractured**	**Heavily Fractured**	**Rubble Pile**
Description	Asteroid is mildly fractured but is still a coherent body. If fractures break through the asteroid, no fragments have moved or rotated from their original positions.	Asteroid is broken into pieces by significant, multiple fractures. Fragments have moved or rotated into different places creating more void spaces.	The asteroid's original body was completely disrupted and the different-sized bits and pieces have reassembled into a gravitationally bound body.
Tentative Porosity Range	0-15% based on comparisons with ordinary chondrite meteorite samples	15-30% based on comparisons with lunar and terrestrial impact samples	>30% based on comparisons with unconsolidated terrestrial sediments, lunar regolith, and reassembly models

Stronger impacts can cause an asteroid to be pervasively fractured. Wilkison and colleagues call this heavily fractured. The fracturing is so intense that multiple cracks crisscross the body, and fragments have slipped or rotated into different places. This creates void spaces in the asteroid, increasing its porosity. Comparing to samples from lunar and terrestrial impact craters, Wilkison and colleagues estimate that the porosity would be 15 to 30%.

Extremely strong impacts can blast an asteroid to smithereens, sending the fragments far from each other. However, there is a range of impact potencies that do not catastrophically disrupt an asteroid. Instead, an impact will bust an asteroid apart, but not impart enough energy to the fragments to cause them to lose gravitational track of each other. The fragments, or at least a large percentage of them, fall back to the center of mass of the system, creating a reassembled pile of rubble. The disorganized pile would be highly porous. Wilkison and team suspect it would be as porous as unconsolidated terrestrial sediments (like sand) or the lunar regolith, so porosity would be greater than 30%.

Rubble Piles

The rubble pile concept has been quite popular among asteroid experts, though not universally accepted. Theoretical simulations of asteroid impact histories suggest that rubble piles should be fairly common. Data on the cooling rates of ordinary chondrites argue strongly that the process happens: Some chondrites are called "regolith breccias." These are rocks reworked by impacts on the surfaces of asteroids. They contain grains of metallic iron-nickel. It is possible to determine how fast these metallic particles cooled by measuring their compositions and sizes.

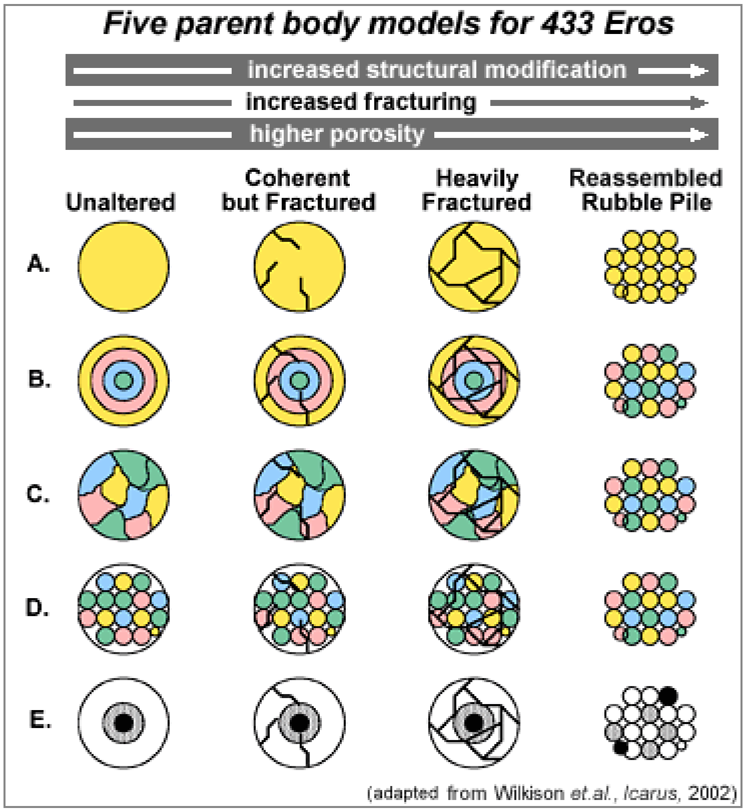
Numerous analyses indicate that in a given regolith breccia, the metallic particles cooled at rates ranging from 1 to 1000 ^{o}C per million years. Using the laws of heat conductivity, we can calculate how deep a rock must be buried to cool at a given rate. The range of cooling rates of the particles in regolith breccias indicates original burial depths of a few kilometers (those cooling at 1000 degrees per million years) to 100 kilometers (those cooling at 1 degree per million years). Clearly, the asteroids on which these breccias formed are jumbled.

At first glance, one would think that craters of different sizes could dig up rocks from a large range of depths and deposit them onto the surface where they could be incorporated into regolith breccias. It is not so easy, however. Jeff Taylor and his colleagues calculated that craters large enough to excavate rock from a depth of 60 kilometers would demolish asteroids smaller than 500 kilometers in diameter [See **PSRD** article: Honeycombed Asteroids.] The easier way to deposit rocks from great depths and to mix them with rocks from shallow depths is to bust up the asteroid and reassemble it into a rubble pile.

This does not mean that any given asteroid, such as Eros, is a rubble pile, however. In fact, we do not know how common rubble piles might be. Wilkison and colleagues tested whether Eros is a rubble pile or a less fractured asteroid.

Putting It All Together: Asteroid Formation and Change Through Time

Asteroids may have had a variety of initial states soon after they formed. The bodies were then modified by impacts as discussed above, leading to different outcomes as shown in the diagram below.



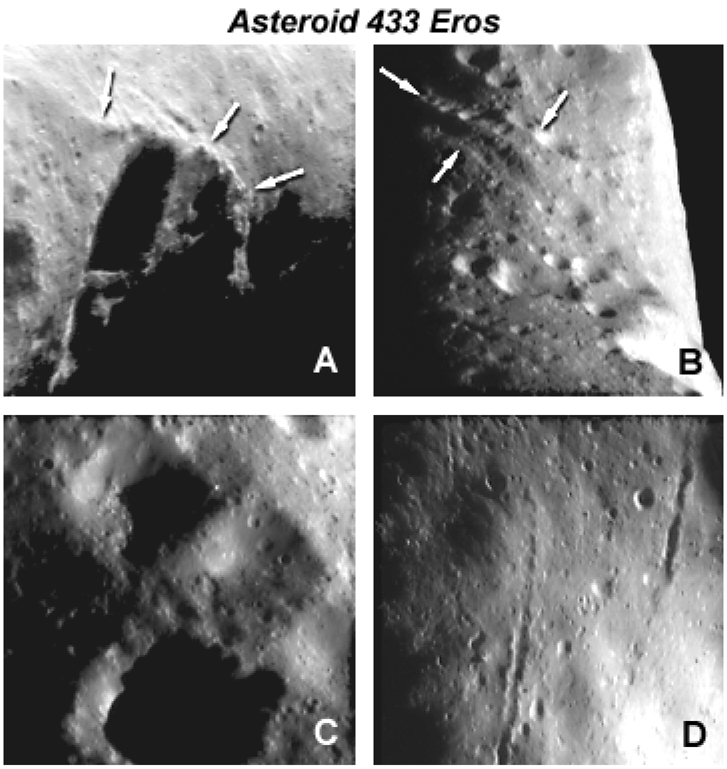
This cartoon shows five models for Eros (labeled A through E) and how each body changes with increased fracturing. Shapes and sizes of fragments are not to be taken literally. Colors represent different chondritic material.

Case **A** depicts the seemingly simple case where an asteroid formed from uniform material and was only very modestly heated. There is no layering or internal structure. Such objects might be relatively weak, but if large enough (bigger than about 50 kilometers in radius), their strength will be governed by their gravity, not the strength of the rock. It is not clear how porous such bodies might be initially. **B** is nicknamed the onion shell model. This applies to asteroids that formed cold and were heated and metamorphosed. This process reduced the initial porosity, especially in the center where temperatures were highest. The degree of metamorphism decreases from the center to the surface. **C**, the heterogeneously heated model, is like case **B** except that the heating was not even throughout the body. The extent of metamorphism is patchy. **D** is called the metamorphosed planetesimal model. It depicts the heating as taking place in numerous relatively small bodies (less than 10 kilometers in diameter). Each of the bodies has an onion-shell structure, but they accrete randomly into the final asteroid. **E** is the case where the asteroid was heated hot enough to melt. If melted to a high temperature it could differentiate into a core, mantle, and crust. Less melting would lead to a body with a crust and a mantle that still contained at least some metallic iron. In either case, **E** is a coherent, strong asteroid.

Asteroids in general, and Eros in particular, are heavily cratered and thus fractured, but it is not easy to choose which parent body or structural model shown in the figure above applies to Eros. That's why Wilkison and colleagues used the additional parameter of porosity to help infer the structure inside Eros.

How Broken Up is Eros?

A macroporosity of 20% for Eros is consistent with values obtained from impact breccias found on the Earth and the Moon, leading Wilkison and coauthors to conclude that Eros is a heavily fractured body. The estimated porosity value does not seem low enough to match the coherent yet fractured model nor high enough to justify calling Eros a reassembled rubble pile. Ridges, troughs, and grooves on the surface of Eros seen from orbit suggest a consolidated and extensively fractured interior but one with enough structural strength to support such features. A prominent ridge system, called Rahe Dorsum, in the northern hemisphere indicates major structural buckling perhaps due to impact-induced compressional shock waves.



(from Wilkison *et.al.*, *Icarus*, 2002)

These images show surface features on Eros which may be indicators of global internal strength. **A:** arrows point to Rahe Dorsum ridge system, **B:** arrows point to twisted ridge, **C:** square craters may have resulted from impacts into preexisting fracture patterns, and **D:** grooves and aligned pits.

It seems that Eros is not a rubble pile, unless it is composed of only a few large fragments. Other asteroids might be, though. To find out how many it will be necessary to send spacecraft to numerous asteroids to determine their densities and chemical compositions, and derive their porosities. Perhaps such measurements could lead to efficient ways of determining the internal structure and strength of asteroids. This would be very useful in assessing the danger of asteroid impact and in figuring out how to deflect an asteroid menacing the Earth. The strategy used to deflect a rubble pile might be drastically different from that used to deflect a fractured asteroid.

Wilkison and colleagues' work shows the value of interdisciplinary research on asteroids and asteroid samples (meteorites). It would not have been possible without the database of laboratory measurements of meteorite densities and porosities or without the spacecraft measurements of Eros.

Additional Resources

NASA's NEAR mission homepage.

NEAR data mosaics and movies from Mark Robinson and team at Northwestern University.

Consolmagno, G. J. and Britt, D. T. (1998) The density and porosity of meteorites from the Vatican collection. Meteor. Planet. Sci. 33, p. 1231-1241.

Flynn, G J., Moore, L. B., and Klock W. (1999) Density and porosity of stone meteorites: Implications for the density, porosity, cratering, and collisional disruption of asteroids. Icarus 142, p. 97-105.

Japan's Muses-C mission will land on an asteroid and bring back samples.

Solar System Exploration: Missions to Asteroids

Taylor, G. J. "The Composition of Asteroid 433 Eros" PSR Discoveries Feb. 2002 <http://www.psrd.hawaii.edu/Feb02/eros.html>.

Taylor, G. J. "Honeycombed Asteroids" PSR Discoveries Aug. 1999 <http://www.psrd.hawaii.edu/Aug99/asteroidDensity.html>.

Wilkison, S. L., Robinson, M. S., Thomas, P. C., Veverka, J., McCoy, T. J., Murchie, S L., Prockter, L. M., and Yeomans, D. K. (2002) An estimate of Eros's porosity and implications for internal structure. Icarus, v. 155, p. 94-103.

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